COMPACT, HIGH-EFFICIENCY, ENERGY-RECYCLING ILLUMINATION SYSTEM

(1) Field of the Invention

This invention relates to illumination systems for projectors, exposure systems, and other devices requiring a laser or lamp source, and specifically relates to illumination systems in which it is an important requirement to make the spatial uniformity of the beam high and the utilization of the light very efficient.

(2) Background of the Invention

A key subsystem in numerous optical systems for a variety of applications is an illumination system which comprises a light source, such as a laser or a lamp, and several optical components, such as mirrors and lenses, to collect, shape and relay the light from the source to the desired destination. For example, in a projector, light from an arc lamp is collected, made uniform, and made to illuminate an object, such as film or a programmable spatial light modulator,

which is then imaged onto a display screen. As another example, in a laser lithography system, light from an excimer laser is collected, made uniform, shaped into a specific cross-section, is made to illuminate a photomask having a pattern, the mask being then imaged by a projection lens onto a substrate such as a semiconductor wafer or a display panel, coated with a layer of a photosensitive medium.

In all of these applications, the intensity of the light illuminating the object must be very uniform spatially. The object, as stated earlier, is, for example, a spatial light modulator (SLM) chip in a projector, or a photomask in a lithography system. Spatial uniformity of a light beam means that the cross-sectional profile of the intensity must be substantially flat. A second important requirement on the illumination system is that its efficiency must be as high as possible so that loss of light is minimized and the smallest possible lamp or laser light source may be incorporated in the optical system, or, alternatively, the highest possible energy may be obtained at the destination surface, such as the display screen or the semiconductor wafer.

Other highly desirable features in an illumination system include compact size and self-luminosity. The importance of a compact size of the illumination

system is self-evident -- it enables the whole optical system to be compact, and therefore, low-weight, more portable, etc. Self-luminosity of a light source means it is equivalent to an emission surface on which every point behaves effectively as an emission point from which light rays emanate in a specific numerical aperture. Such a characteristic is especially important when the illuminated object must be subsequently imaged with high resolution onto another surface. All of the above desirable features of illumination systems are important in the case of digital projections, lithography systems, and numerous other optical systems.

A widely used device for uniformizing the beam in an illumination system is a homogenizer in the shape of a light tunnel with a square, rectangular or hexagonal cross-section. Rays of an input light cone undergo multiple reflections between pairs of parallel mirror strips, causing random mixing of the rays and thereby uniformizing the beam. Such devices are employed in a variety of exposure systems and projectors.

In color projectors, the illumination beams of the three primary colors (red, green and blue) are produced by separating the broad-band (white) light of an arc lam or a halogen lamp by a segmented color wheel. Such a wheel, in a given

position, allows only one of the colors to be transmitted, the others being blocked and lost. In a lithography system, the laser light incident on a mask is only partially utilized -- only that portion of the light which falls on the transmissive regions of the mask is imaged by the projection lens and reaches the substrate. The majority of the light that falls on the opaque portions of the mask is blocked and lost.

An effective technique to minimize the loss of light described in the preceding paragraph is an "energy-recycling" homogenizer. Such a device has an apertured mirror at its input face. The cone of light from the source (lamp or laser) enters the homogenizer through the aperture and is uniformized by multiple reflections as in the conventional light-tunnel homogenizer. However, light rays reflected back from the color wheel (in a color projector) or the photomask (in a lithography system) are made to enter the homogenizer in the backward direction. These rays, when reaching the internal mirror surface surrounding the aperture at the input plate, are re-reflected to travel in the forward direction again, thus being re-utilized.

In all such illumination systems using a light-tunnel type of homogenizer, the longer the homogenizer, the more the number of reflections within, the

greater the mixing of the rays, and therefore, the greater the uniformity of the output beam. However, an undesirable feature of such a homogenizer is that the size of the illumination system becomes larger. This is especially a significant disadvantage in the design of electronic projectors, for which small size of the illumination module is a highly attractive attribute, so that they can be made more compact, lower-weight, and more portable. This invention discloses novel illumination systems with very compact, high-efficiency, energy-recycling beam homogenizing devices. It also discloses compact homogenizing modules as beam-combining devices for efficiently combining the outputs of two or more light sources. Dividing a single input beam into multiple beams is also described.

Summary of the Invention

This invention provides a compact homogenizer by reconfiguring a light-tunnel type of homogenizer such that its straight length is folded multiple times in a zigzag fashion. The total length of the unfolded light-tunnel is such that the desired number of reflections are obtained for the required level of intensity uniformization. The folding of the light-tunnel converts the long configuration of

the conventional device into a very compact module. Additionally, the input beam may be split into two or more beams, each of which may go through a folded homogenizer, and the separate folded homogenizers may be combined into one module by making their last arm common. Each beam entry port -- one, two, or more, as the case may be -- has an apertured mirror at its input face for energy recycling. The multi-port device may also be used as a beam combining device for adding the output of two light sources without the use of devices such as beamsplitters. When used as a compact energy-recycling homogenizer in an illumination system, the multi-port configuration provides greater beam uniformity and smaller size.

For entry into the port, light from a lamp source is collected by a curved mirror, such as an ellipsoidal mirror, and focused near the entry aperture of the port. For entry into multiple ports, the collected light is collimated and split into multiple equal beams by tilted flat slabs or rhombs which deviate and displace the component beams which are then focused by individual lenses. Light from a laser source is likewise focused, or split and focused, into the entry ports.

The exit face of the compact homogenizer acts as the effective source plane that is self-luminous and emits into the desired numerical aperture. The

exit face is imaged onto the relevant "object" of the rest of the optical system, e. g., a spatial light modulator or a photomask.

The reflecting inner surfaces of the homogenizer may be mirrored surfaces or coated with multilayer dielectric films designed for high reflectivity. Alternatively, the homogenizer tunnels may be constructed of a solid optical material, such as glass, fused silica, or acrylic, in which reflections at the walls take place by total internal reflection. Each of these configurations of the compact, high-efficiency, energy-recycling illumination system is described in detail in the section "Detailed Description of the Embodiments."

Brief Description of the Figures

Fig. 1 is a schematic illustration of a compact, high-efficiency, energy-recycling illumination system having a beam homogenizer with two entry ports and made in a hollow configuration.

Fig. 2 shows details of the construction of a compact, hollow homogenizer with two entry ports.

Fig. 3 shows the different components that make up the dual-port, hollow homogenizer of Fig. 2.

Fig. 4 shows the head-on views of the input and output faces of the homogenizer of Fig. 2.

Fig. 5 is an illustration of a compact, high-efficiency, energy-recycling, solid homogenizer constructed of an optical material such as fused silica, glass or acrylic.

Figs. 6 and 6A show, respectively, the head-on views of the input and output faces of the homogenizer of Fig. 5.

Fig. 7 is a schematic illustration of the four beam-splitting optical elements of Fig. 1 configured into one composite element for ease of fabrication.

Fig. 8 illustrates a compact, single-entry-port homogenizer of hollow construction, and light from a lamp source collected and coupled into it.

Fig. 9 is an embodiment showing a compact, solid homogenizer with a single entry port and slots cut to form separate beam-uniformizing channels.

Fig. 10 illustrates a hollow quad homogenizer with four entry ports for reducing the beam intensity in each arm and for combining multiple beams.

Figs. 11 and 11A show head-on views of the input and output faces of the quad homogenizer of Fig. 10.

Fig. 12 illustrates a solid embodiment of the quad homogenizer of Fig. 10,

showing four entry ports and slots cut to separate the different internally reflecting channels.

Fig. 13 presents the homogenizer embodiment previously shown in Fig. 8, here illustrating the problem of handling the central ray bundle.

Fig. 14 illustrates the inclusion of a small indented cone on the exit face of the homogenizer to deflect the central rays at a desired angle to enable their collection.

Fig. 15 presents a compact solid homogenizer whose reflecting arms have a hexagonal cross section.

Figs. 16 and 16A show the head-on views of the hexagon-shaped solid homogenizer of Fig. 15.

Fig. 17 shows a more compact configuration of a hexagon-shaped solid homogenizer.

Figs. 18 and 19 show the head-on views of the input and output faces of the hexagonal homogenizer of Fig. 17.

Fig. 20 illustrates an embodiment of a square solid homogenizer with embedded construction in which the innermost reflecting channel is surrounded by channels of square-ring-shaped cross-section.

Fig. 20A presents a side view of the homogenizer of Fig. 20, showing the slot cuts that separate the three embedded reflecting channels.

Fig. 21 shows a different embodiment of the square embedded homogenizer with the middle square-ring-shaped channel turned by 45 degrees to make the construction more compact.

Fig. 22 is a head-on view of the input face of the homogenizer of Fig. 21.

Fig. 23 is an embodiment of the embedded solid homogenizer with circular channels.

Fig. 24 is a side view of the embedded circular solid homogenizer of Fig. 23.

Fig. 25 is an illustration of a solid, embedded circular homogenizer similar to that of Fig. 23 but with a square innermost channel to produce a square illumination field.

Fig. 26 shows a solid, embedded circular homogenizer similar to that of Fig. 23 but with a hexagon-shaped innermost reflective channel to produce a hexagonal illumination field.

Fig. 27 illustrates the function of a multi-port compact homogenizer as a beam-combining device, showing two beams of specified numerical apertures

entering the unit and exiting as a uniform, combined beam of the same numerical aperture.

Fig. 28 illustrates the function of the multi-port compact homogenizer as a beam-dividing device, showing a single beam of a specified numerical aperture entering the unit and exiting as two uniformized beams of the same numerical aperture.

Detailed Description of the Embodiments

A preferred embodiment of the invention is illustrated in Fig. 1. Light from a lamp 1 as light source is collected by curved reflector 3 and is directed toward two optical rhomb elements 5 and 7. Although rhomb elements are shown as a preferred method of beam splitting, other devices, such as tilted optical flats, will also provide the necessary function. The curved reflector is designed to provide a nearly collimated beam of light. Although it is preferred that the curved reflector make the collected beam collimated, it is not essential, for collimation may be easily accomplished by a simple lens element. The two rhombs 5,7 are placed in close proximity so as to receive nearly all the light from the lamp source 1. As shown in Fig. 1, the input beam gets split in two separate beams by the

rhombs 5,7, which displace the two beams laterally and direct them parallel to the original optical axis. To further identify the different beams, rays 9 and 10 are part of the full beam, whereas rays 11 and 12 are each part of one of the split beams.

Each of the split beams is focused by a focusing lens 14 or 16 near the entrance of the two aperture ports 18, 20 of the compact homogenizer assembly 22. The focusing lenses 14 and 16 focus the light rays into a specified angle, for example angle 24, that defines the numerical aperture of the light bundle.

Compact Homogenizer Construction

The compact homogenizer assembly 22 is made of a set of mirror strips and mirrored glass plates. Alternatively, it may also be made of a solid block of a suitable optical material, such as glass, fused silica or acrylic. Details of the construction of the homogenizer module are illustrated with the help of Figs. 1 and 2. I first describe the construction using mirror strips and plates. This results in what I shall call a "hollow homogenizer." Referring to Fig. 2, the input face of the hollow homogenizer is a mirror strip 26 whose inside surface is mirrored. It has two holes 18, 20 which serve as entry ports for the two focused cones of

light, as illustrated in Fig. 1. This input face mirror strip is shown separately in Fig. 3. The output face of the hollow homogenizer is comprised of two mirror strips 28, 30 whose inside surfaces (i. e., those facing the strip 26) are mirrored. As can be seen in Figs. 1, 2 and 3, the planes of the input face mirror strip and the output face mirror strips 28, 30 are vertical, and perpendicular to the primary optical axis of the device, which axis is horizontal. Between the input face mirror strip 26 and the output face mirror strips 28, 30 are six horizontal mirror strips, shown as 32, 33, 34, 35, 36 and 37. The mirror strips 32 and 37 are mirrored on the inside, whereas the strips 33, 34, 35 and 36 are mirrored on both sides. Note that mirror strips 33, 34, 35 and 36 are shorter in length than mirror strips 32 and 37. In the assembled state, the left edges of strips 33, 36 are in contact with the input face of strip 26, whereas the right edges of strips 34 and 35 are in contact with, respectively, the output face mirror strips 28 and 30.

All of the above mirror strips 26, 28, 30 and 32-37 are mounted as sandwiched between mirrored glass plates 39 and 40. This is more clearly illustrated in Fig. 4, which shows the head-on views of the input face strip 26 and the output face strips 28, 30. The assembly of all of the above components may be accomplished by a suitable adhesive.

Compact, Solid Homogenizer Construction

We next describe the construction of the compact solid homogenizer according to the invention. As shown in Fig. 5, the solid homogenizer is made from a single block 41 of a suitable optical material, such as fused silica, glass or acrylic. In this solid block 41 are made four thin slots 42, 43, 44 and 45 and surfaces thus formed are polished smooth by chemical means or mechanical means or by a combination of the two. These slots then help define the five solid arms of the zigzag tunnel. Additionally, the input face ABCD of the solid block is coated with a metallic layer to be highly reflective except for two small circular regions 47, 48, which serve as the entrance "ports" for the input beams. Note that these "holes" in the metallized surface provide entry for the input beams into the solid body of the two arms (uppermost and lowermost) of the homogenizer. The exit faces of the homogenizer are also mirrorized, as are the upper, lower and side faces. The output channel of the homogenizer is shown as 49 in Figs. 6 and 6A, which present the head-on views of the input and output faces of the solid homogenizer configuration. Note that the exit face of port 49 is not mirrored; in fact, it is preferable to coat it with a multilayer anti-reflection coating.

Reflection of light rays in the channels of the solid homogenizer takes place by total internal reflection (TIR). This phenomenon takes place when the input numerical aperture is such that the angle of incidence of all rays striking each surface parallel to the optical axis is greater than the critical angle, which is given by

$$\alpha = \sin^{-1} (1/n),$$

where n is the index of refraction of the solid material. In almost all applications, this condition is readily satisfied. When it is not, the horizontal surfaces can be mirrorized. I remark that mirrorizing the horizontal surfaces (along with the vertical surfaces) may be advantageous even when total internal reflection is feasible.

Reduction in Number of Components

The embodiment in Fig. 1 shows four optical elements in the light collection part of the illumination system. These four optical elements may be fabricated as one single unit, as illustrated in Fig. 7. Note that the four elements of Fig. !, namely the rhombs 5, 7 and the lenses 14, 16, are combined into one unit 52 in Fig. 7. Thus, with the light collection and shaping module of Fig. 7 and

the homogenizer module of Fig. 5, the entire optics for the illumination system may be reduced to two subassemblies, recycling/combining homogenizer subassembly 41 and beam separating subassembly 52.

Compact, Single-Entry-Port Configuration

An important advantage of the dual-entry-port configuration of Figs. 1, 2 and 5 is that the total light energy is channeled into two paths, and therefore, the intensity in each path is halved. This is beneficial because there will be less heating of the walls of the homogenizer, as well as its bulk material in case of the solid homogenizer configuration.

In many applications, the total intensity of the beam from the source may not be very high; consequently, heating of the surfaces or the bulk of the homogenizer may not be an issue. In such a situation, a homogenizer with a single entry port may be a preferred configuration. Such an embodiment is shown in Fig. 8. It shows the homogenizer 53 with three arms configured in a reversed S-shape. The homogenizer has one entry port 54 into which light from lamp 55 is focused by ellipsoidal reflector 56. Uniformized light exits from exit face 57. The construction shown in Fig. 8 is of a compact, single-entry-port,

hollow homogenizer. Fig. 9 shows a solid construction 60 in a fashion similar to the solid construction 53 shown in Fig. 5.

In all configurations of the compact homogenizer, whether with two entry ports (Figs. 1, 2, 5) or with one entry port (Figs. 8, 9), and whether of hollow construction (Figs.1, 2, 8) or of solid construction (Figs. 5, 9), the light emerging from the exit port (e.g., 31 in Fig. 1 or 57 in Fig. 8) is directed toward an object plane. This may be, for example, a spatial light modulator chip in a projector, or a photomask in a lithography tool. This is done by a projection lens, which images the exit port of the homogenizer onto the object. This is illustrated in Fig. 1, where projection lens 27 images the exit port 31 onto spatial light modulator chip 29, after folding by fold mirror 25.

Compact Quad Homogenizer

An embodiment of the invention as a quad homogenizer is shown as 62 in Fig. 10. Compared to the two entry ports in the configuration of Fig. 2, this embodiment has four entry ports 63, 64, 65 and 66. Each pair of oppositely situated entry ports accepts light cones in two of the four arms, and the entering rays are randomly mixed to achieve the beam uniformization. Note that some

rays entering in one pair of opposing ports and traveling in the corresponding five hollow channels may reflect into some channels corresponding to the other pair of entry ports, but substantially all rays eventually emerge from the exit port. Figs. 11 and 11A show the head-on views of the input face and output face of this hollow quad homogenizer.

A solid embodiment of the quad homogenizer is shown as 68 in Fig. 12. This is made of a solid block of a suitable optical material, e. g., fused silica, glass or acrylic. Its construction is similar to the embodiment shown in Fig. 5, except that now there is another set of entry ports and corresponding channels in which light rays mix randomly by total internal reflection. As mentioned in reference to Fig. 5, the homogenizer of Fig. 12 may be mirrored on all its surfaces, except for its entrance port holes and exit port, for cost-effective construction. Further, it would be advantageous to coat the entrance port holes and the exit port with an anti-reflection coating to eliminate the approximately 4% loss that occurs in transmission through uncoated glass surfaces.

Treatment of Central Rays

I illustrate how the invention utilizes the central rays (i. e., those emitted by the lamp along the primary optical axis). As shown in Fig. 13, a central ray 69 would enter the homogenizer through the entry port 54, travel parallel to the horizontal surfaces, strike mirrored wall 28, and would be reflected back out through the entry port, thus never reaching to the second arm of the homogenizer, and therefore being lost. This loss is prevented by the technique illustrated in Fig. 14. The central ray 69 travels parallel to the optical axis and strikes the back reflecting surface. In the region where the central ray 69 strikes the back surface, there is a small, conical indentation 70 whose surfaces are mirrored. The central ray 69 will hit a wall of this conical indentation and be reflected at an angle β. The angle of the indent cone is so designed that the angle β is equal to the angle of the light cone entering the homogenizer. Thus, the central ray is effectively utilized and, moreover, its angular position is maintained within the original cone of light, thus preserving the NA-preserving property of the homogenizer. Note that Fig. 14 has illustrated this embodiment for a solid homogenizer; it is likewise implemented for a hollow homogenizer, with a similar cone on the mirrored wall of the output face. The base diameter of

the cone may be of the order of one-tenth of the width of one channel.

Compact Homogenizer with Hexagonal Cross-Section

The embodiments presented in Figs. 1-14 show a square or rectangular cross-section of each of the light tunnels. This invention also lends itself well to configure shapes of light tunnels other than rectangular or square. Fig. 15 illustrates an embodiment with hexagon-shaped channels according to this invention. An illumination beam with a uniform hexagonal cross-section is of great benefit in seamless scanning exposure systems in which consecutive scans with the hexagonal beam provide overlapping complementary exposure dose to enable seamless and uniform exposure of a large-area substrate.

A compact, solid, hexagonal homogenizer 72 is shown with three arms, similar to the rectangular embodiment of Fig. 9. The input light cone enters through entry port 73. Reflecting walls between the channels are realized by slots 74, 75 which result in total-internal-reflection surfaces as in the embodiments of Figs. 5, 9 and 12. The head-on views of the input and output faces of the homogenizer are shown in Figs. 16 and 16A. Note that the exit port

is the face 76 of the bottom tunnel, and it is unmirrored, and preferably anti-reflection coated.

Another embodiment of the hexagonal construction is shown in Figs. 17, 18 and 19. The homogenizer 77 has slots 79, 80 and 81 to separate the reflecting tunnels. Light entering through entry port aperture 78 is uniformized by multiple bounces first in arm 82, then in arm 83, and finally in arm 84, from which it exits.

Homogenizer Embodiments with Embedded Channels

Building on the concepts described in the preceding pages and illustrated in Figs. 1-19, it is logical to conceive many additional embodiments. Two such embodiments, which use embedded internally reflecting channels, are shown in Figs. 20 and 21. In Fig. 20, a square channel is embedded in a second square-ring-shaped channel that surrounds the first channel, and the second channel is embedded within an even larger square-ring-shaped channel. Light cones enter through entry ports as before. Separation between channels is also achieved as before by slots -- except in this embodiment the slots are also square-ring-shaped. A side view is shown in Fig. 20A, which also shows a representative ray

path 85.

Fig. 21 shows the square embedded configuration with the middle square-ring-shaped channel so arranged that its reflecting surfaces parallel to the optical axis make a 45° angle with the other two channels. Fig. 22 shows a view of the front face of the unit.

An embodiment with three embedded circular channels is shown in Fig. 23, and its side view in Fig. 24. Fig. 24 shows a representative ray path 86. An embodiment with a square innermost channel and two surrounding circular-ring-shaped channels is shown in Fig. 25. A similar embodiment with a hexagonal innermost channel is shown in Fig. 26.

Beam Combining

A very useful function of the multi-port embodiment of the present invention is its ability to combine the beams from two or more sources into a single beam without the use of a beamsplitter, without any loss from additional elements, and without altering the numerical aperture. As shown in Fig. 27, Beam 1 and Beam 2 enter the beam combining homogenizer 87 into their respective entry ports with the specified numerical apertures. The rays from the

two beams get randomly mixed by the multiple reflections in the homogenizer channel arms and emerge as a single bundle 88 with the same numerical aperture.

This useful function is of great interest in numerous applications in optics and materials processing with lasers. For example, in some applications, higher fluence is needed than available with one laser source. The device of this invention enables adding the beams from multiple laser sources. If desired, two sources of different wavelengths can be added to be incident collinearly on the same object surface. Such is the situation, for example, when one beam is meant for causing a process to take place in a material, whereas the other beam is such that it is desired that it not cause a process to occur, being for viewing or illumination only. Yet another application involves the addition of two beams such that the fluence from one beam is just below the threshold for a process to occur, and the other beam causes the transition to a regime in which the process takes place. As will the evident to one skilled in optics or processing, such a beam-combining device will be useful in numerous other applications.

Beam Division

From the illustration of Fig. 27 and the discussion of beam combining, it is at once evident that the device of Fig. 27 can be used in an optically reversed direction to serve as a beam-dividing device. The embodiment of the invention as a beam-dividing device is illustrated in Fig. 28. Such an optical module is useful as a beam divider 89, when, for example, a high-power light source is to be shared by two lithography systems, each receiving a share of the total power from the source as a respective one of beams 90 and 91.

It is evident that many additional configurations may be visualized without departing from the spirit and scope of the invention.

CLAIMS: